Muon Systems

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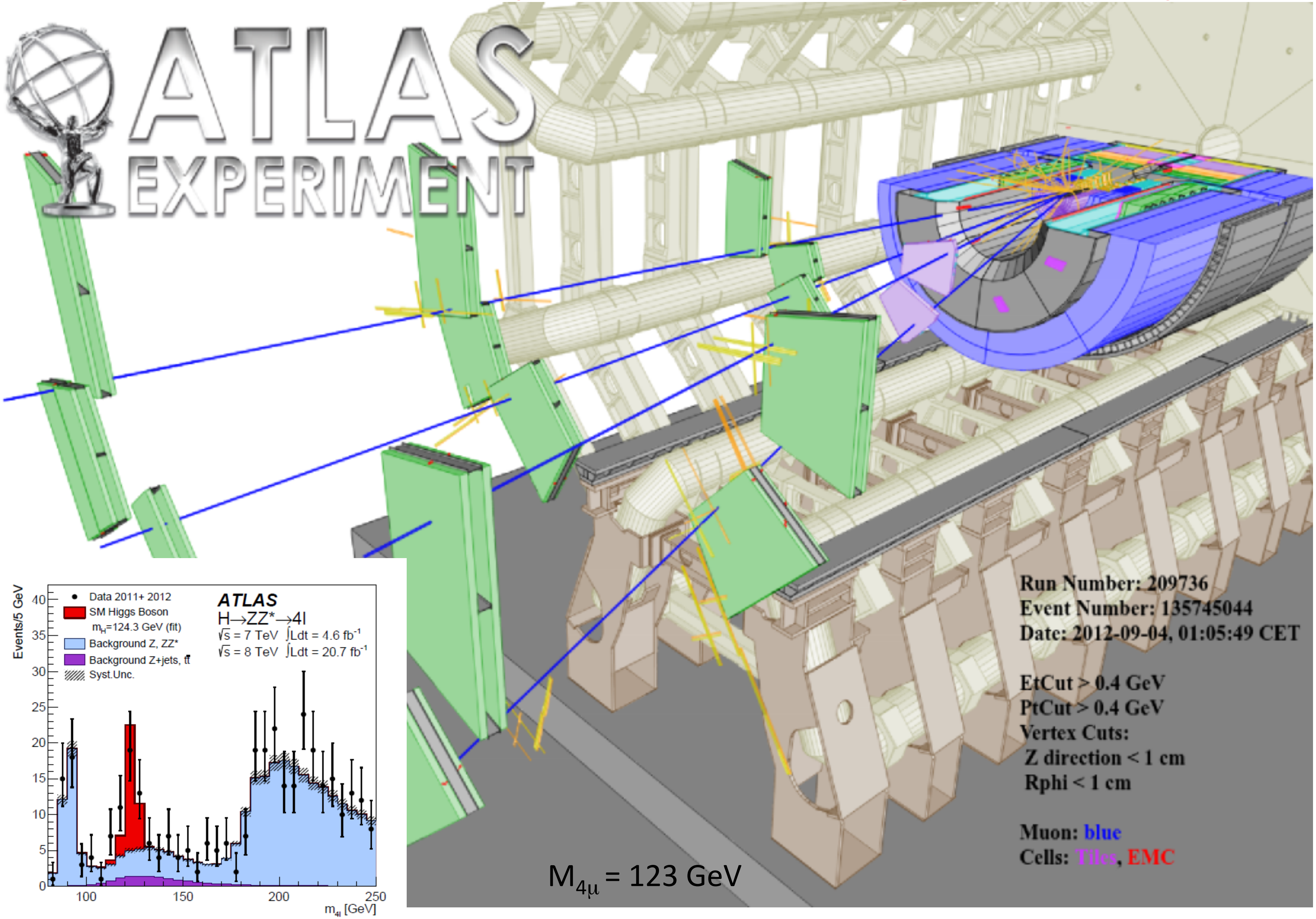
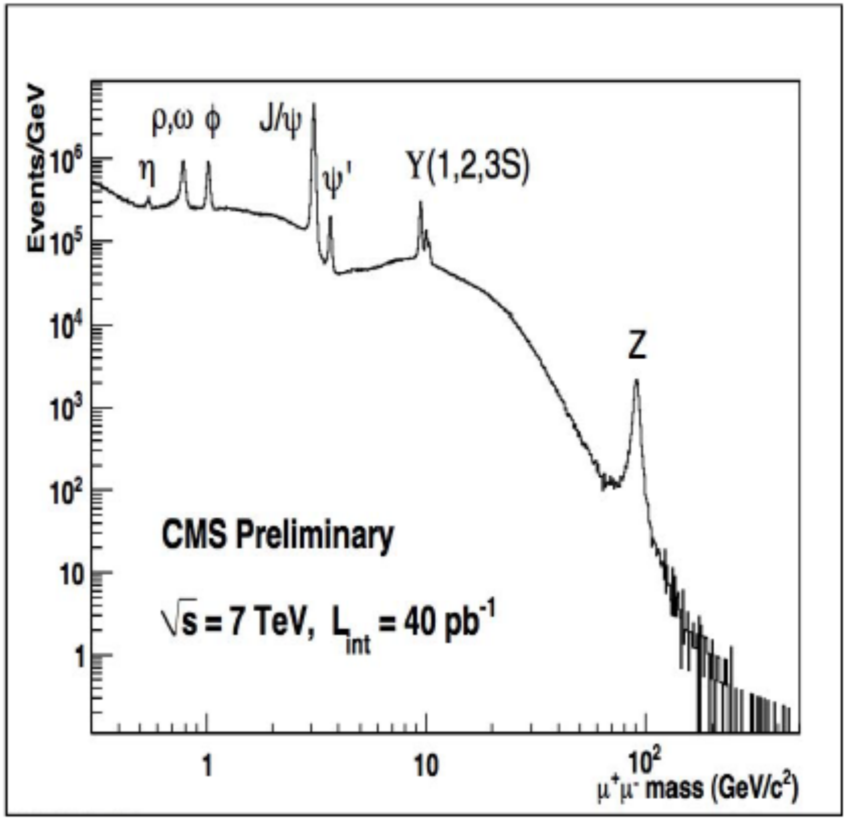
Muons, fundamental probes in searching for New Physics



Impressive Dimuon Spectrum Measurement

CMS



Muon Systems
Important Physics Discovery Tool

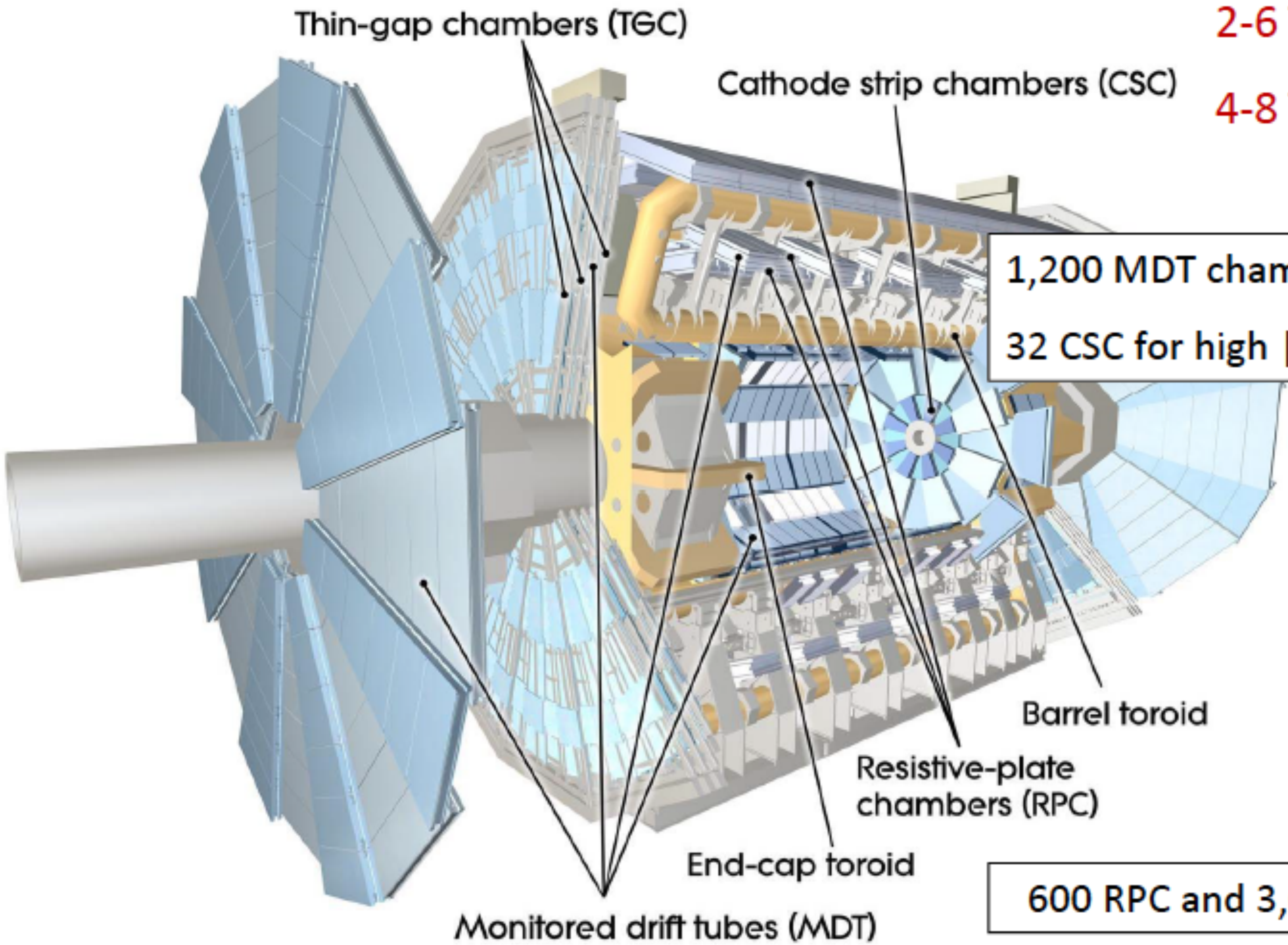
Define size of Detector

Will cover mostly Detector and Electronics R&D needs for muon Systems. For an overall excellent talk on all aspects of muon Systems see: Frank Taylor's talk at:
https://indico.fnal.gov/conferenceOtherViews.py?view=standard&confId=7864

For options on magnets, cost, etc, see also H. TenKate's and W. Riegler's talks at:
http://indico.cern.ch/event/340703/

ATLAS Muon System

ΔpT/pT < 10% up to 1 TeV



2-6 Tm |η|<1.3

4-8 Tm 1.6<|η|<2.7

1,200 MDT chambers for tracking

32 CSC for high |η| region

Diameter 24 m
Length 45 m
W(B) = 1.0 GJ

600 RPC and 3,600 TGC trigger

Challenging even at LHC

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  - High Spatial Resolution – e.g. with an integral BdL of, say, 4 Tm the sagitta of a 200 GeV (P_T) muon at high eta is about 0.5mm, a 10% DP_T/P_T measurement requires resolution of better than 50 μm
  - Comparable resolution in detector alignment over 20 or so meters
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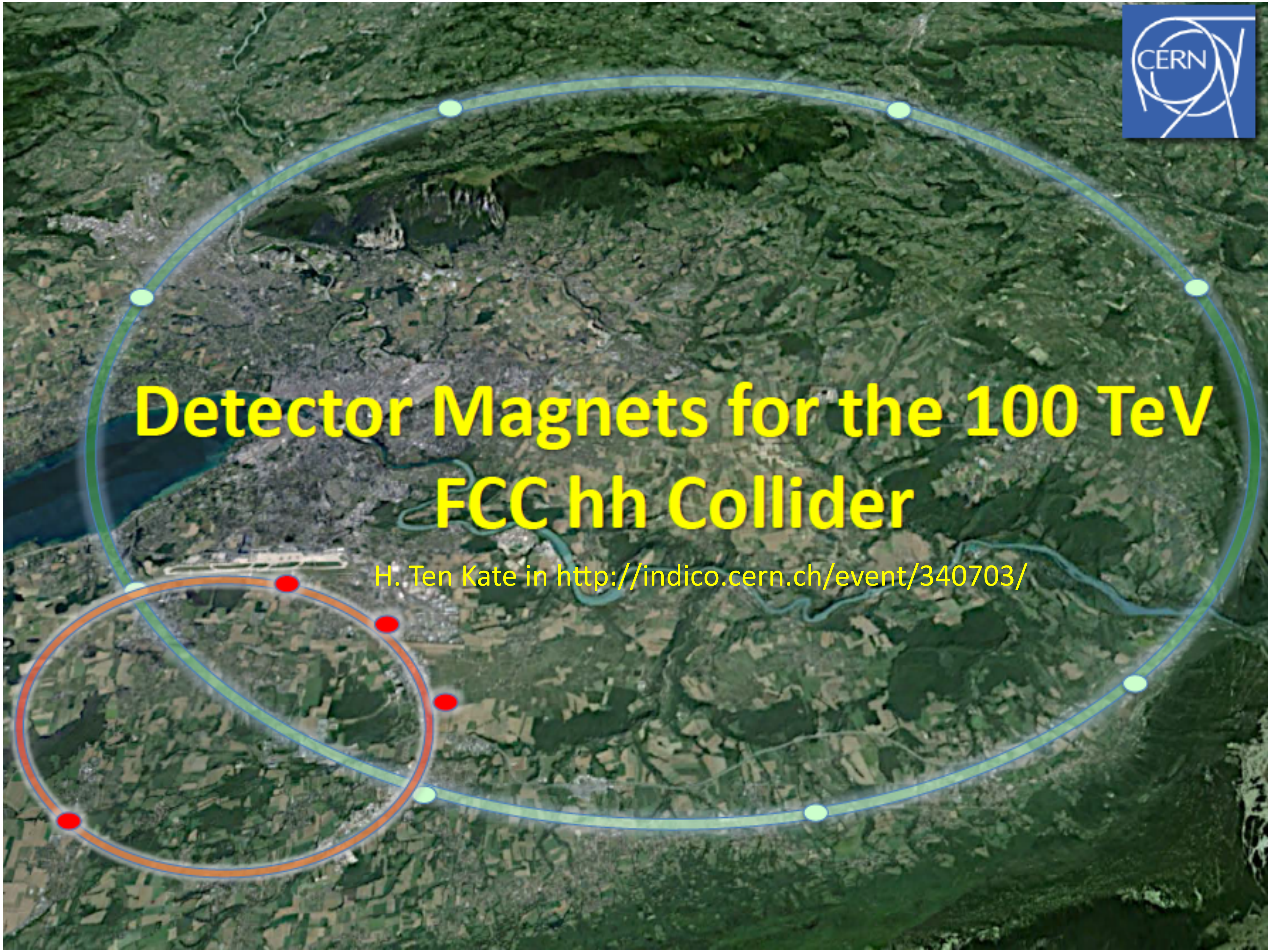
Detector Magnets for the 100 TeV
FCC hh Collider
H. Ten Kate in http://indico.cern.ch/event/340703/
CERN

The Future pp Collider (100 TeV FCC?)

- As an example of what may be driving Detector/Electronics R&D for Muon Systems in the next several decades
- Scaling Factors wrt LHC*:
  - E_{CM} 14 TeV → 100 factor of 7
  - Total Inelastic cross section 80 → 108 mb, factor 1.35
  - Particle Density 5.4 → 8 per unit η, factor 1.48
  - Average transverse momentum/particle 0.6 → 0.8 GeV/c, 1.33
  - Transverse Energy increase by a factor of 2
  - Pseudorapidity coverage (maintain, say, ATLAS $|\eta|<2.7$) → $|\eta|<3.2$

  - Min. bias events will be very similar to those at the LHC

  - For muons Background drives much of the design of electronics/DAQ and it scales with E_{CM}
  - Uncorrelated background then ~10 times present →~50 kHz/cm^2 worst case

(more on correlated background later)

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Detector Technology Choice

Muon Chamber Technology	Deployment	Comments
Drift Tubes with field shaper electrodes	Barrel Tracking & Triggering Cell resol'n ($r\phi$) < 250 μm	CMS
MDT (Monitored Drift Tubes) 3 cm dia.	Barrel Tracking Tube resol'n ($r\theta$) ~ 150 μm resolution	ATLAS
Small Diameter MDT 1.5 cm dia.	Tracking in some special regions of barrel	ATLAS
Cathode Strip Chambers (CSC)	Endcaps Tracking & CMS Triggering ATLAS: η strip pitch 5.5 mm, ϕ strip pitch 13 - 21 mm	CMS and ATLAS ($2<\lvert\eta\rvert<2.7$)
Micromegas	Endcaps Tracking & Triggering Readout pitch ~ 0.4 mm	ATLAS Phase I Upgrade New Small Wheel
Thin Gap Chambers (TGC)	Endcaps Triggering & Tracking 2nd coordinate	ATLAS 1st and 2nd stations Endcap
Small-strip Thin Gap Chambers (sTGC)	Endcaps Triggering & Tracking Fast enough for BC tagging 95% τ < 25 ns; 3 mm strip-pitch	ATLAS Phase I Upgrade New Small Wheel
Resistive Plate Chambers (RPC)	Barrel and Endcaps Triggering Fast τ ~ 3ns ATLAS: η strip pitch ~ 30 mm, ϕ strip pitch ~ 30 mm	ATLAS and CMS
Low Resistivity RPC	Higher rate capability 10^{10} Ωcm	R&D
Multi-gap Resistive Plate Chamber	Very fast τ ~ 50 ps	ALICE and R&D
GEMs (3 layer)	Endcaps Rate ~ 10^5Hz/cm^2 Fast τ ~ 4-5 ns	CMS Phase I Test & Phase II

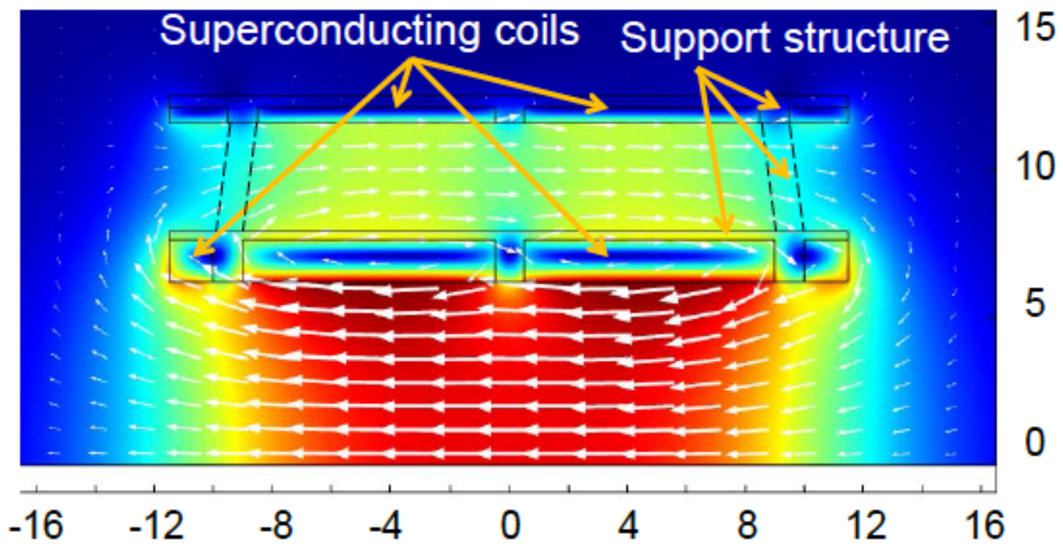
Georges Charpack

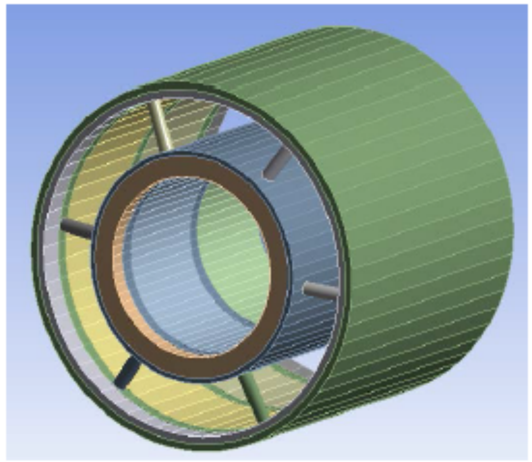
From F.Taylor's talk, see slide #3

Detector Technology Choice (cont.)

- It will certainly have to be some sort of gas detectors
  - Coarser granularity in Barrel, e.g., large diameter drift tubes, or other electron drift-type chambers
  - Much finer granularity needed at Endcaps, CSC, sTGC, Micromegas, etc
- Technologies dating back half a century, but advances in Electronics make it possible to meet demands of today’s Exps.
  - MWPC invented in 1968: For several decades wire readout provided ~1 mm resolution adequate for the needs of most experiments of the time
  - 1990s cathode strip charge interpolation provide an order of magnitude better resolution. Cathode readout was mentioned in Charpack’s original paper but had to wait for more advanced electronics
- “Measure muons in Air” school of thought ca 1990? Results in impractical systems if extrapolated to the FCC
- But CMS proved that measuring muons in Tracker possible thanks to advanced technology (Si tracker) and electronics   (see dimuon spectrum in slide 3)

2. Twin Solenoid - Cold Mass Concept





- Stored energy 54 GJ, conductor stored energy density: 12.6 kJ/kg.
- 6.0 T in center, 6.3 T peak field in turns, Conductor 4 kt, cold mass: ≈ 6 kt.
- 1.4 m thick inner coil and 0.4 m thick outer shielding coil.
- Large forces resulting from minor misalignments between the coils.
- Support cylinders and spokes are essential parts of the cold mass.
- 2.6 T in 3.5 m gap between solenoids for muon trackers.
- 5 mT line at 28 meters radius.

From H. TenKate's talk, see Slide #7 for reference

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Spatial Resolution

Life gets much tougher for muons

$$\frac{\Delta p}{p} \propto \frac{p}{BL^2}$$

Unlike electrons

$$\frac{\Delta E}{E} \propto \frac{1}{\sqrt{E}} + k$$

But Momentum Calibration at 20 TeV
Is straight forward (linear system)

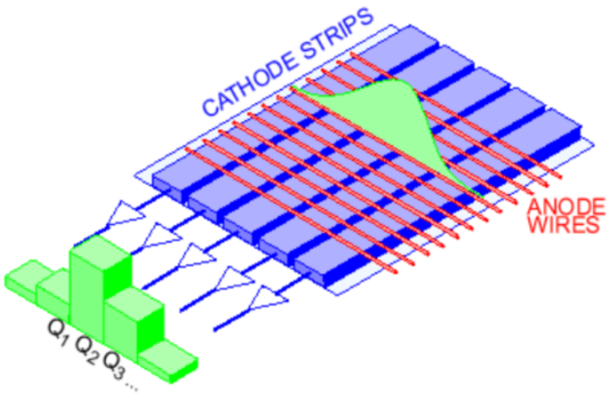
Not so for Calorimeters
How does one calibrate jet E scale?

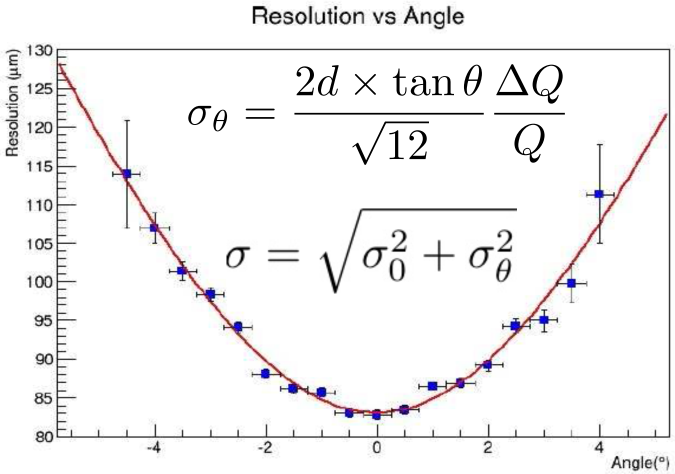
- ❑Tracking point resolution of 100 microns rms possible today
- ❑If similar resolution is to be maintained, BL2 is scaled by a factor of 7
  - ❑Not easy, not cheap
- ❑ Perhaps use a combination of B,L, detector resolution improvement to achieve something closer to x7
- ❑Several detectors quote spatial resolution <<100 microns rms, but…

…. may be true for tracks at normal incidence

❖MWPC with cathode strip charge Interpolation (CSC, sTGC,-MWPC with graphite cathodes)

❖Resolution depends on angle of incidence, deteriorates rapidly

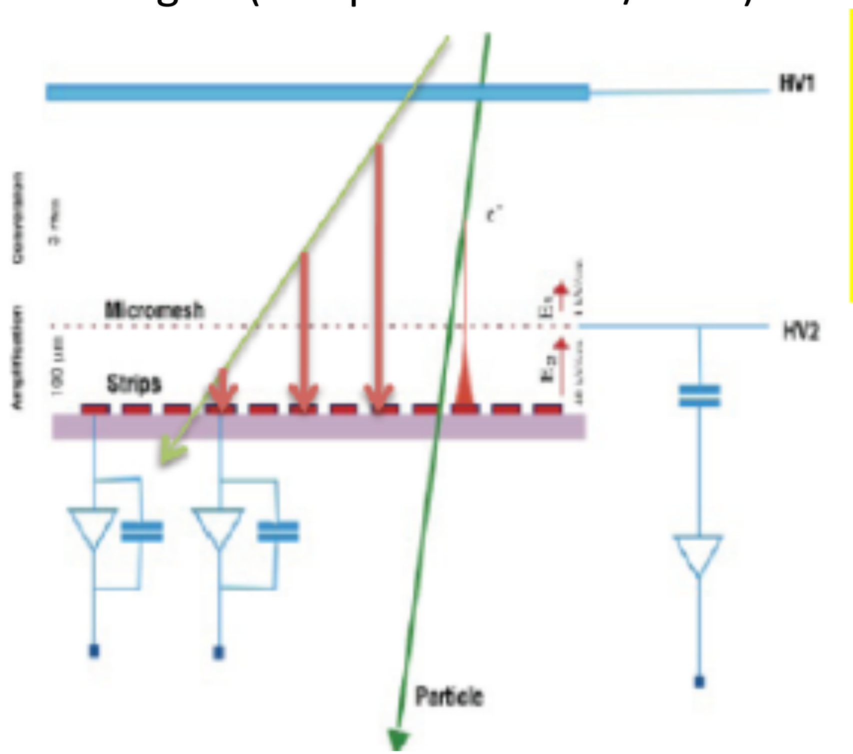




Micromegas (ATLAS), GEM (CMS) Upgrades

◆Charge barycenter does not work as well

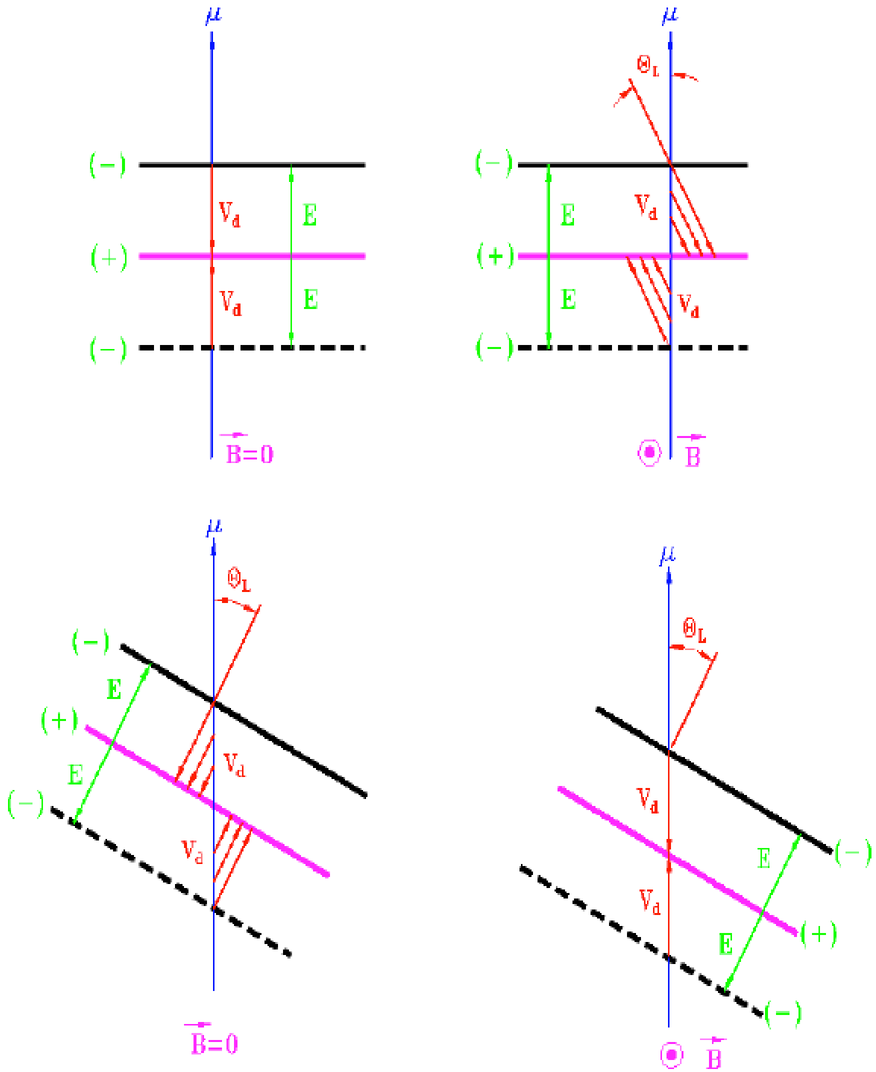
◆Fine pitch (due to small charge footprint determined by transverse diffusion, ~ 300 μm) may provide adequate resolution in a "micro-TPC mode", but resolution deteriorates at small angles (complements CSC/sTGC)



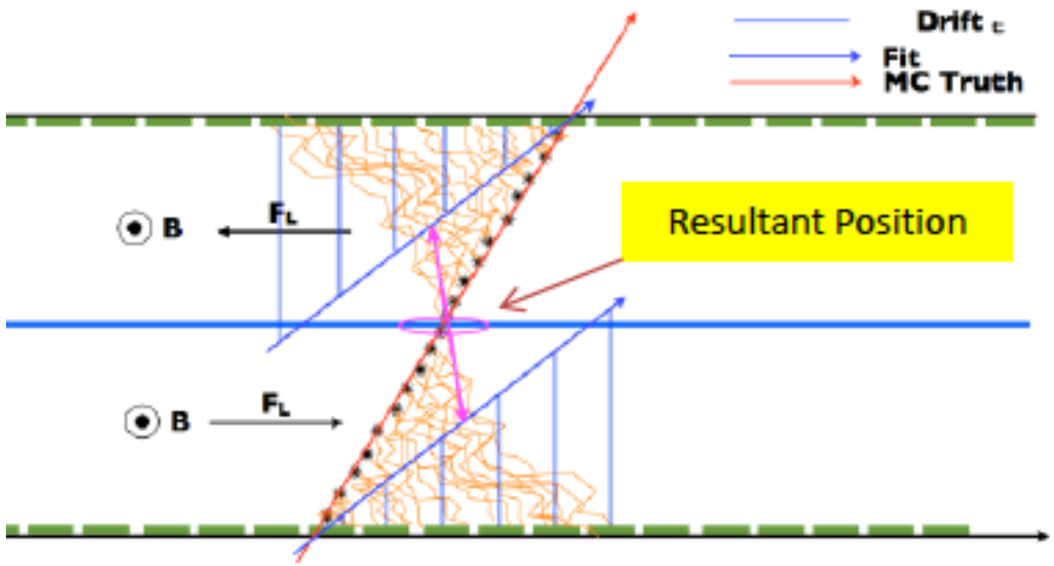
Note: Drift Tubes are immune to angle of incidence

….Also Lorentz Angle in Magnetic Field

In CSC or sTGC detectors rotate chambers by the Lorentz angle. Works for solenoidal Geometry. Does not work with toroids (would require a spherical arrangement of detectors!



Mitigation in Micromegas/GEM by arranging back-to-back detector planes



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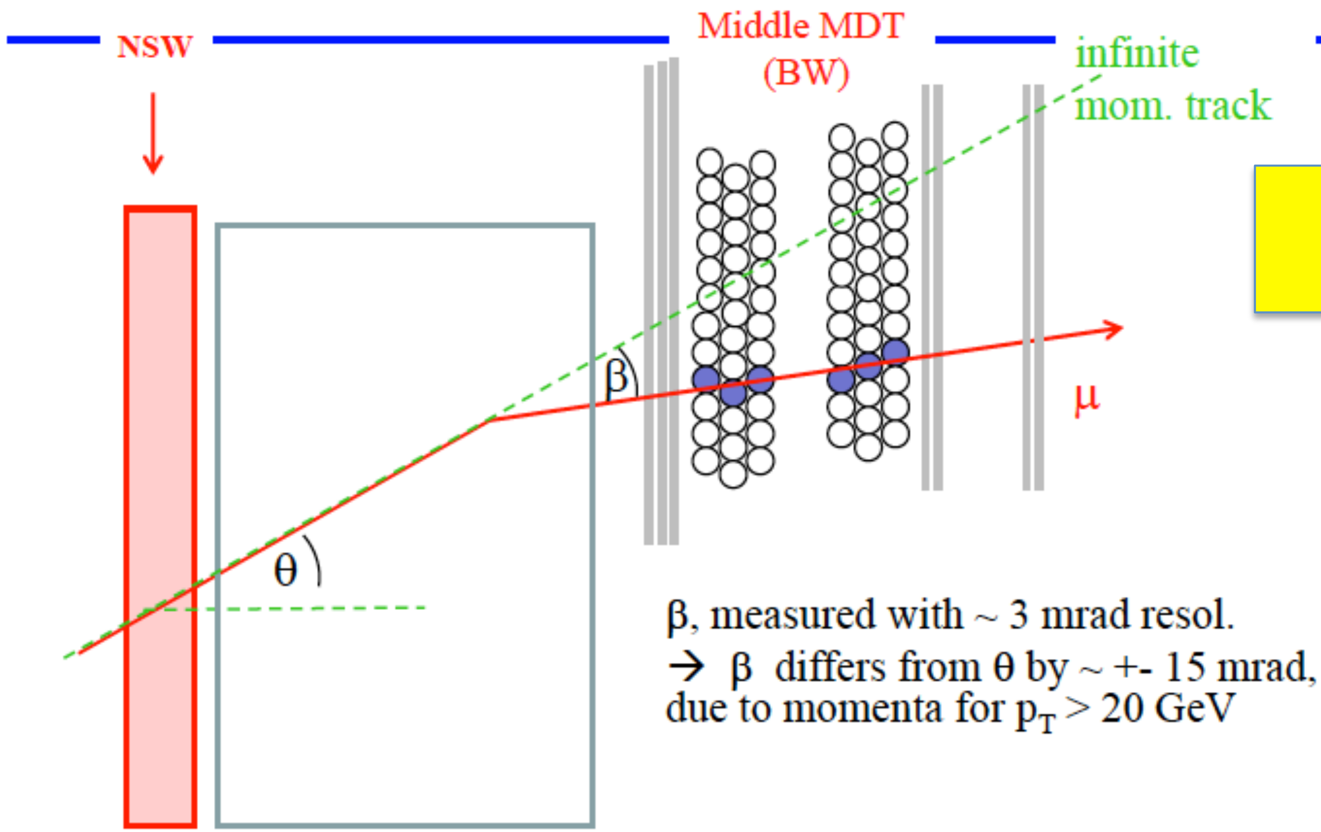
Separate Detectors for Precision Measurement and Trigger?

- Most Systems in Experiments up to-date have detectors with separate trigger and precision measurement functions
  - drift chambers + Resistive Plate Chambers (RPC) , e.g.,ATLAS Barrel
  - drift chambers + Thin Gap Chambers (TGC – ATLAS Endcaps)
  - Dual Function Detectors also used (Cathode Strip Chambers, CMS Endcaps)
    - Charge interpolation in cathode strips provides adequate spatial resolution, OR of several wire planes results in ~ 4 ns timing resolution, adequate for BC identification.
    - Even so they were also complemented by RPC
- Present LHC Systems designed in 1990ties
  - Custom ASICs included just the front end of signal processing
  - Tight Level-1 trigger latency made it impossible for drift detectors to participate in the trigger
  - Both ATLAS and CMS for the Upgrades consider detectors that can do both (ATLAS Micromegas, TGC – CMS GEM
- Future Systems must have dual function detectors to limit cost and complexity – How can we improve?

An example (ATLAS MDT) considered for Phase2

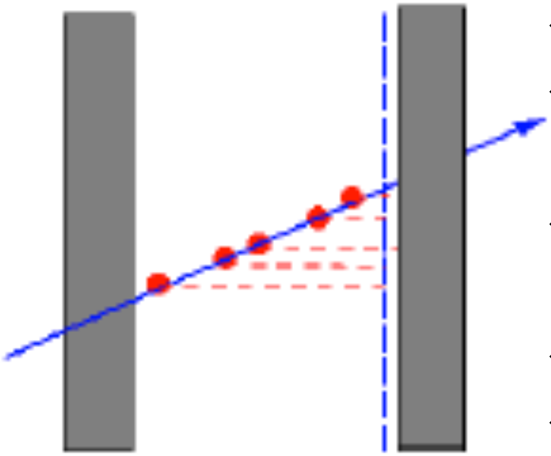


From R. Richter
(MPI, Munich)

Use the High Resolution Drift Tubes at Level 1 Trigger
Processing time (6 usec) not compatible with Phase 1 latency (2.5 usec)
Implementation in FPGA, but
A new front end and time digitizer will be necesssary

The Electronics Challenge of a MM Trigger

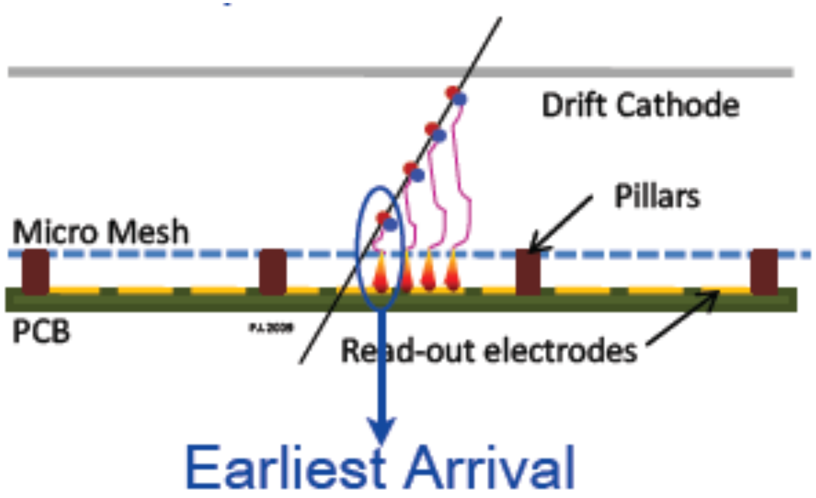
- ❖ The Small (~0.3 mm FWHM) charge footprint of the μMegas detectors results in excellent position and double track resolution (important for handling correlated background)
- ❖ Results in a very large number of channels (~2x10^6)
- ❖ Two Functions of the Readout:
  - Provide Precision measurement of charge and time at Trigger Level 1 accept
  - Provide in real time vector with ~1 mrad resolution to improve P_T Resolution in PhaseII
- ❖ First task relatively easy to accomplish by highly multiplexed, data driven system (not different than e.g. a Si Vertex Detector)

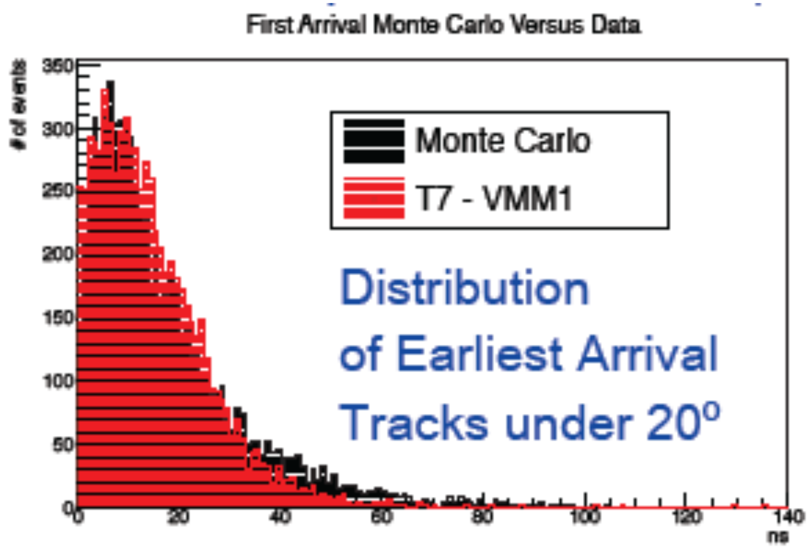


- ❖ Take advantage of the 0.5 mm pitch
- ❖ From each 64-Channel IC consider ONLY the earliest arriving hit for every bunch crossing
- ❖ Effectively a 30,000 channel system with granularity of 3.2 cm (64x0.5 mm) but resolution of order 0.5 mm
- ❖ Logic ignores other hits in this BC
- ❖ Probability of second hit during processing time (2-3 BC)<1%

MM Trigger Concept (cont.)

- Ionization collision, avalanche fluctuations, etc smear the timing of the earliest hit but nearly all events contained within 2 BC
- Use a 2 or 3 BC rolling window to look for BW matching tracks

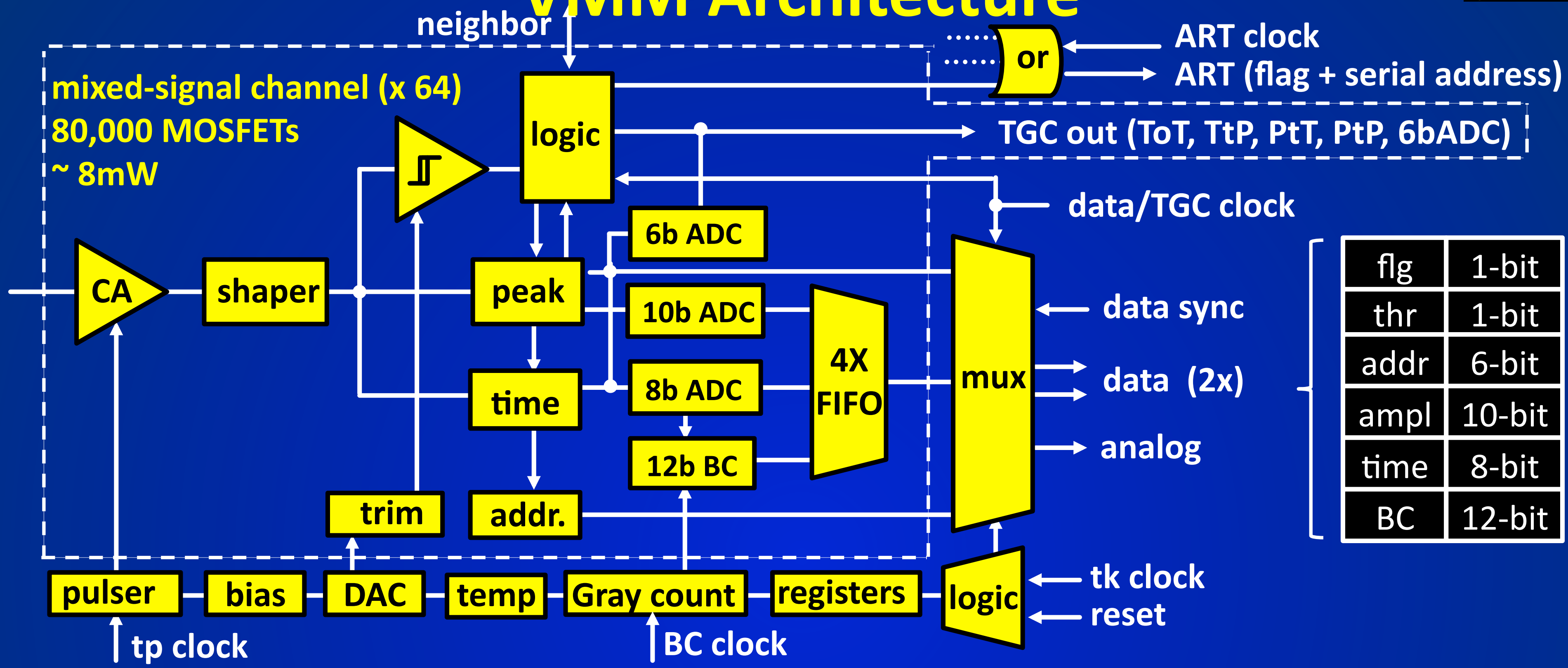




Front End Development

- A new ASIC is being developed (G. de Geronimo, BNL, Instr.Div.)
- 64 Channels
  - Includes 3 ADC per channel
    - 10-bit fro peak amplitude, multiplexed
    - 8-bit vernier time stamp (20-bit effective) multiplexed
    - 6-bit, 25 nsec conversion serially out, all 64 channels in parallel
- Four Independent data output paths
  - Mmegas Trigger (ART)
  - sTGC Trigger (6-bit ADC, 25 ns conversion, or pulse output, selectable)
  - Digitized, multiplexed Amplitude and Time for both detectors
  - Analog, multiplexed Amplitude and Time measurement (requires external digitization, left over from earlier version)
- "System on a chip"

VMM Architecture



- adj. polarity, adj. gain (0.5,1,4.5,6,9,12,16 mV/fC), adj. peaktime (15,50,100,200 ns), test, mask
- sub-hysteresis discrimination, trimming, channel and chip neighboring
- real-time address (ART) with flag, dual-edge serialized
- peak detector, time detector, analog memories
- 64 direct TGC outputs (ToT, TtP, PtT, PtP, 6-bit ~25ns ADC dual-edge serialized)
- multiplexed analog outputs, serialized address, token passing
- 10-bit ~200ns ADC peak, 8-bit 100ns ~ADC time, 12-bit BC t-stamp, 4x channel FIFO
- dual channel multiplexed digital output, dual-edge serialized with sync signal
- analog monitor, pulse generator, Gray-code counter, temp. sensor, PROMPT (ITAR)

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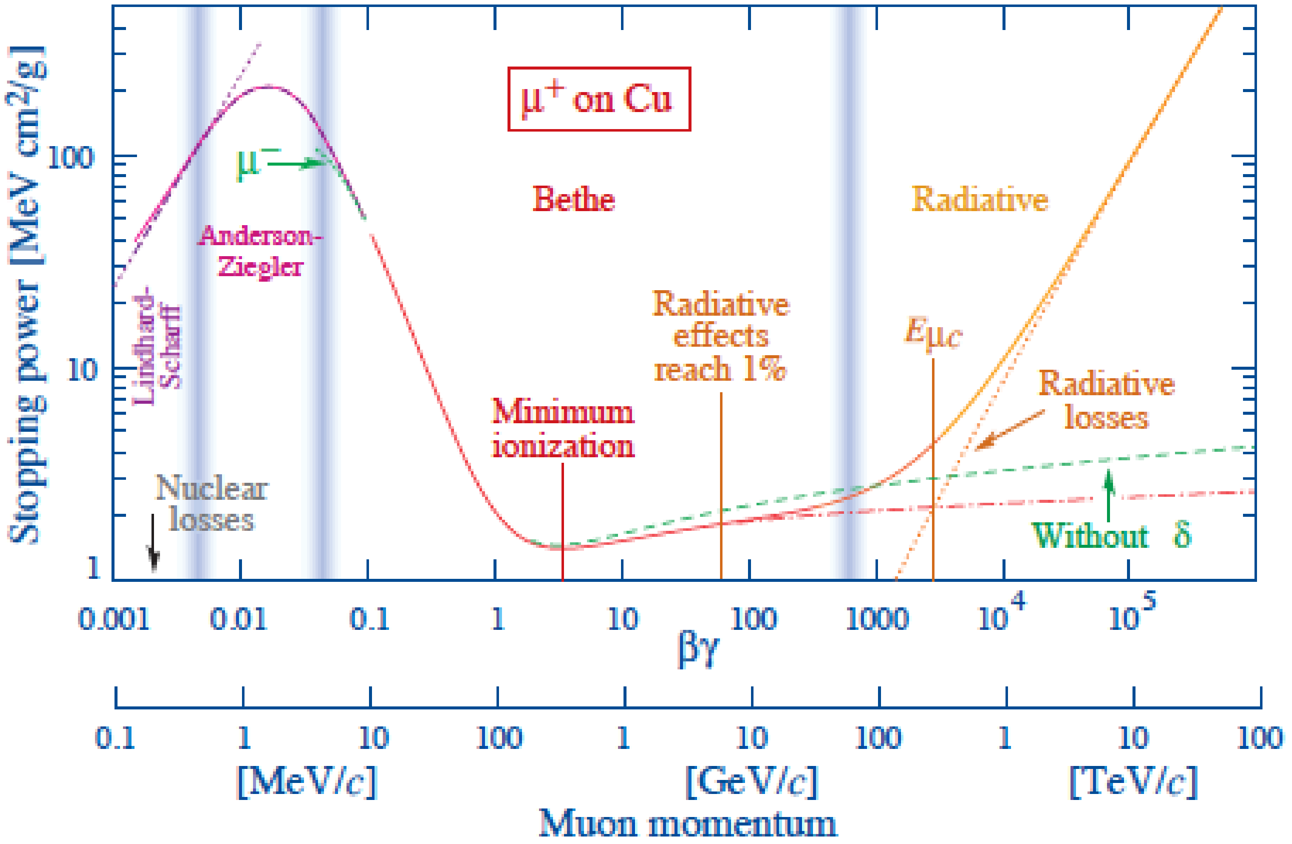
Background

- High (uncorrelated) background (photons, neutrons) at 50 kHz/cm^2 level might not be so difficult to handle
  - Most hits are single plane hits
  - ~15% segments from Compton electrons, charged particle background not originating in IP
- Requires highly segmented (=lots of channels) tracking detectors
- More serious is the correlated background
  - Radiative em debris accompanying high momentum muons
  - Already visible at ~100 GeV/c muons
  - Muon critical energy in iron ~800 GeV
  - Serious problem in measuring multi-TeV muons

Correlated Background from Radiative Energy Loss

(From the Particle Data Book)



Mitigation Strategy?

❖Allow space between absorber and detector planes for greater space separation
❖Highly segmented Detectors with excellent double track resolution
❖Micromegas detectors with very small charge footprint may do it?
❖Many millions of channels, but so what? More sophisticated electronics
❖Measure muons before calorimeters?

Concluding Remarks

- Not likely that other than gas detectors can be used in future Muon Systems
  - Highly segmented dual function detectors (trigger and precision measurement)
  - R&D to improve resolution could pay off
  - R&D in high precision alignment systems
- Measure Muons before the Calorimeters (a la CMS)?
- Would result in huge number of electronic channels
  - Learn not to be afraid of channel count
  - Development of sophisticated electronics
  - Front end ASICs that do both functions
  - Much of data processing on-chip (System-on-a-chip)
  - Take advantage of developments like lpGBT, high speed links, commercial devices
  - Commercial devices, whenever possible, for the back end will result in easy, cheap, upgrades as more powerful versions emerge.